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TNO report

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NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road

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Contents

1 Introduction

This document contains results from emission tests, carried out by TNO in the period 2010-2015[1]. The specific focus is on NO_x emissions of Euro 5 and Euro 6 diesel passenger cars. The emission tests were carried out as part of a project conducted by TNO for the Dutch Ministry of Infrastructure and the Environment.

This report presents a detailed overview of test results for individual vehicles. With this report TNO intends to provide clarity and understanding on the measured data and what they do and do not imply. TNO and the Dutch Ministry of Infrastructure and the Environment aspire to provide maximum transparency on the information that feeds into policy decisions regarding air quality and emission legislation.

Overall results of the project have been published between 2010 and 2015 in the reports listed in chapter 7. The results presented in this report are fully consistent with results presented in previous reports.

1.1 Objectives of the project

The project, of which the results are presented in this report, is one in a long sequence of projects, carried out by TNO for the Dutch government, to investigate the emission behaviour of road vehicles.

The primary purpose of these projects is to gain an understanding of the emissions of road vehicles in real-world situations under varying operating conditions. The results provide input for the process of establishing emission factors which are used in the Netherlands for policies at the national, regional and municipal level relating to air quality and overall emissions of air-polluting substances.

The insights obtained in the project furthermore serve as input for the activities of the Dutch government and the RDW[2] in the context of decision making processes in Brussels (European Commission) and Geneva (GRPE[3]) to improve emission legislation and the associated test procedures for light and heavy duty vehicles, all with the aim to reduce real-world emissions and improve air quality.

1.2 TNO policy with respect to publication of data

TNO takes the utmost care in generating data and in communication on the findings of its studies, taking into account the interests of the various stakeholders. In the projects, of which the work presented in this document is a part, importers and manufacturers of tested vehicles are informed of the test results of their vehicles, and are given the opportunity to reflect on them.

[1] The report contains results on all Euro 5 and 6 diesel passenger cars tested before May 2015.
[2] Rijksdienst voor het Wegverkeer (the Dutch road vehicle authority)
[3] UNECE Working Party on Pollution and Energy (GRPE)

> In the evaluation and interpretation of test results on individual vehicles the following considerations need to be taken into account:
> - The tests performed by TNO are not intended for enforcement purposes and are not suitable for identifying or claiming fraud or other vehicle-related irregularities in a scientifically and legally watertight way.
> - For each make or model, only a single vehicle or a small number of vehicles is/are tested a limited number of times. This means that it cannot be ruled out that the results correlate to the specific condition of the tested vehicles or to specific test conditions. The latter is especially the case in road-world testing on the road in which a large number of conditions, that have a strong influence on test results, vary from trip to trip (see e.g. section 5.2).

In publications about the emission test results on light duty vehicles TNO has up to now, for reasons as indicated above, chosen to present test results in a way that does not allow makes and models to be identified[4]. Where results of individual vehicles were reported, these were always anonymised.

As part of TNO's constructive contribution to the on-going public debate about the real-world NO_x emissions of diesel cars, TNO has decided to issue this document in which test results are presented with reference to makes and models. This decision also meets a desire expressed by the Dutch Ministry of Infrastructure and the Environment. By presenting results from the complete sample of vehicle models tested, covering a wide range of makes and models, and by providing the necessary background information on test procedures and test conditions as well as caveats with respect to what can be concluded from these data, the test results on individual vehicle models are presented in a context that allows a well-balanced interpretation of the meaning of the results.

Finally, we would like to emphasize that as an independent knowledge institute, TNO is, has been and will be open to constructive dialogue with industry and governments. This is part of TNO's efforts to work together with relevant stakeholders in finding and supporting the implementation of effective solutions to reduce real-world emissions of harmful substances from vehicles, as well to determine and demonstrate the effects of implemented measures in an objective way.

1.3 This report

Tables providing an overview of NO_x emission test results of Euro 5 and Euro 6 passenger cars are provided in chapter 4 of this report. Chapters 2 and 3 provide information on the test procedures used by TNO and the selection of the vehicles. This information is needed for interpretation of the detailed test results presented in chapter 4. For the same reason chapter 5 contains a set of general considerations and specific additional information, which provides the necessary context for the summary of observations and interpretation of results that is provided in chapter 6. Finally chapter 7 gives an overview of previous reports in which results of the test programs carried out by TNO have been published.

[4] See e.g. the references in chapter 7 at the end of this document.

2 Test methods

2.1 Evolution of test methods and protocols

The project on road vehicle emissions, of which the data presented here are a result, is one in a sequence of projects for the Dutch government dating back to 1987. Over time the testing procedures and the test program have evolved with the developments in type approval test procedures as well as available measurement technologies, with developments in the understanding of real-world emissions and with advances in vehicle technology. This is illustrated in Figure 1. Also in the course of the 2010-2015 period the test programme has evolved to ensure that the best available measurement technology and test procedures are used in view of the objectives of the project. As a consequence not all vehicles listed in Table 3 and Table 4 (see chapter 4) have been submitted to the same test programme.

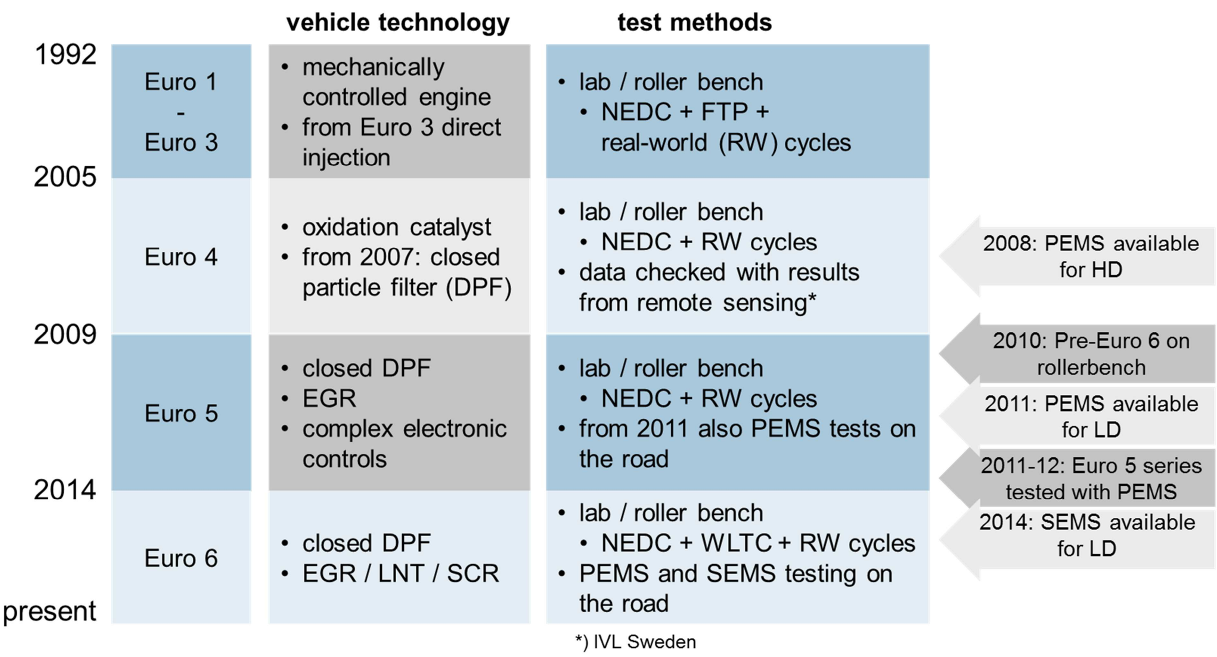


Figure 1 Overview of how the measurement program applied by TNO for testing LD diesel vehicles has evolved together with the evolution of vehicle technology and available test methods

Note: For abbreviations see sections below or chapter 8.

Vehicles have been tested in the laboratory on a roller bench (also known as chassis dynamometer), simulating the vehicle mass and driving resistances, using various driving cycles, as well as on the road using portable emission testing equipment. Overall the vehicles listed in Table 3 and Table 4 have been submitted to one or more of the tests listed in Table 1 below.

Table 1 Overview of tests applied to the Euro 5 and 6 diesel vehicles

Test	Type	Description
NEDC cold start	lab / roller bench	The NEDC (New European Driving Cycle) is used for the official type approval of a vehicle. During an NEDC test with cold start (the so-called Type 1 test) the emissions need to comply with the applicable limit. Non-compliance cannot be concluded from the results of an individual test (see notes in section 5.1).
NEDC hot start		Some vehicles were additionally tested over an NEDC with a hot start to gain more information about the emission performance. This is not part of the official procedure for type approval.
CADC cold start		The CADC (Common Artemis Driving Cycle) is a cycle which better represents real-world driving than the NEDC. The CADC, however, is not part of the official type approval procedure. A cold and hot start are both possible with the CADC.
CADC hot start		
WLTC cold start		Currently a new worldwide harmonized type approval procedure (WLTP) for light duty vehicles is under development, which involves a new driving cycle: the Worldwide harmonized Light duty driving Test Cycle, or WLTC. Most WLTC-tests reported here have been performed with a cold start.
WLTC hot start		Some vehicles were additionally tested over a WLTC with a hot start to gain more information about the emission performance.
PEMS reference - cold start	on road measurements using PEMS (Portable Emission Measurement System)	PEMS and SEMS are emission measurement systems than can be mounted on-board vehicles for measuring emissions on the road under real-world driving conditions. To facilitate comparison of individual real-world test results, the TNO-designed ‘reference trip’ is always part of the investigation (with a cold start as well as a hot start). The reference trip consists of urban, rural and highway driving. Additionally, some other trips are driven, for instance a trip mainly containing urban driving.
PEMS reference - hot start		
PEMS urban - hot start		
PEMS various trips		
SEMS reference - cold start	on road measurements using SEMS (Smart Emission Measurement System)	
SEMS reference - hot start		
SEMS urban - hot start		
SEMS various trips		

2.2 Measurements in the laboratory

2.2.1 Test facilities

Equipment
When testing a vehicle in the laboratory, the vehicle is made to drive a specified speed-time pattern (driving cycle) on a chassis dynamometer (also called: roller bench) which simulates the inertia (mass) and driving resistances (rolling resistance and air drag) of the vehicle.

Except for the vehicles tested in 2010, most of the chassis dynamometer tests on Euro 5 and Euro 6 vehicles have been performed under supervision of TNO at the facilities of Horiba in Oberursel, Germany. Horiba is the manufacturer of certified laboratory test equipment and operates facilities that are qualified to perform tests according to official protocols to the highest industry standards (ISO 17025). The first Euro 5 and Euro 6 vehicles were tested around 2010 at the facilities of PDE Benteler in Helmond. Up to 2015 a 2-wheel chassis dynamometer has been used. From 2015 onwards a 4-wheel chassis dynamometer is used.

In the laboratory emission measurements are carried out in two different ways. For the overall emission results, that are reported in Table 3 and Table 4, the emissions are measured in accordance with UNECE R83 which requires the emissions accumulated over the complete tests to be determined by sampling the diluted exhaust gases collected in large bags. With this method emission behaviour cannot be linked to specific events during driving (such as accelerations or gear shifting).

For determining emission factor models, which are used to predict average real-world emissions of vehicles in a wide range of traffic circumstances, a measurement device is used that records emissions on a second-by-second basis (“modal mass”).

Both test results are frequently compared and only minor deviations were found in recent years. In the past, with the introduction of direct sampling around 2008, large deviations were found, and the second-by-second results had to be recalibrated from time to time to make them suitable for emission predictions.

Chassis dynamometer settings
The mass and driving resistance (road load), which are simulated by the roller bench, can be set in different ways. For replicating the type approval test the applied roller bench settings are the values used by the manufacturer for the type approval, and are obtained by TNO from the vehicle’s type approval certificate or information supplied by the importer or manufacturer. The determination of these road loads is in accordance with UNECE R83.

The vehicle test mass varies between tests. The NEDC test mass, based on prescribed weight classes, is usually the lowest mass at which a vehicle is tested. The WLTP “test mass high”, which includes the additional weight of the vehicle model options and a limited payload, is usually the highest mass at which a vehicle is tested. The differences between these two extremes is about 150 kg for a normal passenger car.

In the test programme variations in test masses have been applied in view of e.g. capturing the influence of mass on emissions for the purpose of determining average emission factors. As a consequence of that, and of limited resources, on different vehicles the mass used with a specific test cycle may have been determined according to different definitions.

As the vehicle tested by TNO is not exactly the same as the vehicle submitted for type approval by the manufacturer, the type approval road load setting may not adequately reflect the actual road load of the tested vehicle. The road load of a vehicle can be independently determined by carrying out a coast-down test on a test track. Some of the chassis dynamometer test listed in Table 3 and Table 4 have been carried out using road load settings determined by TNO with the same vehicle that is tested in the lab.

In general, in recent years, the road load values for the chassis dynamometer settings obtained from the importer or manufacturer are low compared to the findings obtained in a coast-down test program in which these values were determined independently by TNO, carried out in accordance with the official test procedure as described in Regulation 83. In a number of cases the official road-load values, used for type approval, were found to be too low to be realistic. In some

cases the tyres mounted on the production vehicle had a higher driving resistance, as declared in the tyre energy label, than the value specified for the vehicle as a whole.



Figure 2 A vehicle tested in the laboratory on a two-wheel chassis dynamometer (roller bench)

Higher road load values yield higher fuel consumption and CO_2 values, but may affect also the NO_x emissions of the vehicle in two manners: The higher required engine power for the actual production vehicle will lead to an increase in emissions by the basic combustion process. In addition, if a vehicle's engine control system is optimized for the engine powers and speeds associated with a low road load, the engine may have a poor emission calibration for the engine loads occurring in independent tests with production vehicles. Even higher road loads may occur during on road testing, in part due to the added weight of equipment and operator, but largely related to e.g. different road surfaces, steering and ambient conditions.

The Worldwide harmonized Light vehicles Test Procedures (WLTP[5]) has a different test procedure for determination of the road load curve, which results in higher values to be used when the WLTC is driven on a chassis dynamometer.

2.2.2 *Test cycles and test conditions*

NEDC

The New European Driving Cycle (NEDC[4,6]) is the test cycle (speed-time profile) that is prescribed to be used for European type approval testing of vehicle emissions and fuel consumption. The test procedure as a whole is prescribed by regulation UNECE R83[4].

The "NEDC cold start" test is an independent reproduction of the type approval test (the so-called Type 1 test). The roller bench settings (vehicle mass and driving resistance) are the values used by the manufacturer, and are obtained by TNO from the vehicle's type approval certificate or information supplied by the manufacturer.

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[5] See: http://www.unece.org/trans/main/wp29/meeting_docs_grpe.html

[6] See: *Reference book of driving cycles for the use in measurement of road vehicle emissions*, Barlow, T.J., Latham, I.S., McCrae, I.S., Boulter, P.G., (2009), TRL report PPR 354

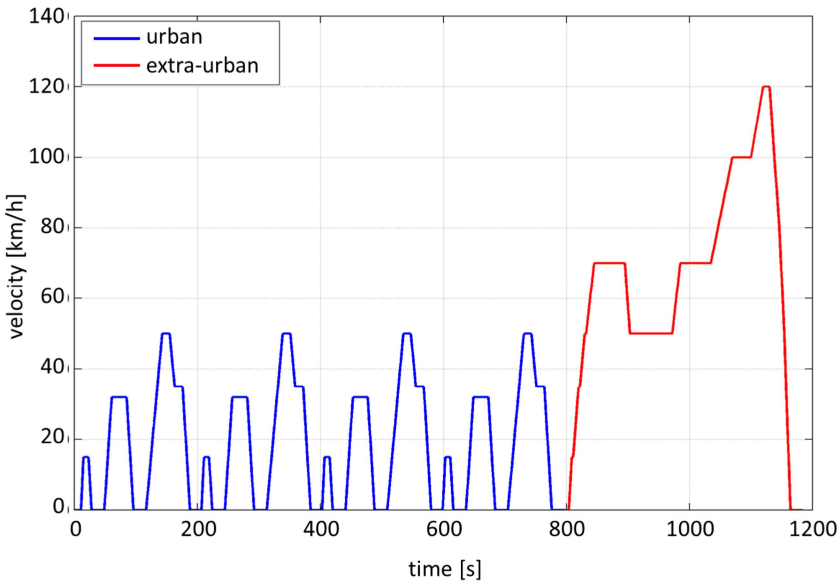


Figure 3 NEDC (New European Driving Cycle)

In the type approval test procedure the emission test is started with a cold engine, a condition obtained by “soaking” the vehicle for at least 6 hours at a temperature between 20 and 30°C. The NEDC test can also be started with a warm engine, i.e. an engine that is at its nominal operating temperature. The test is executed at an ambient temperature between 20 and 30°C. Based on scientific principles, emissions at cold start are expected to be higher than when a vehicle starts a trip with a warm engine and warm exhaust aftertreatment system. Until 2009 (up to “halfway” the Euro 4 timeframe) the effect of a cold start on real-world emissions could be determined by subtracting the emissions measured on an NEDC-test starting with a warm engine from those measured on an NEDC-test with a cold start. This approach was abandoned when Euro 5 diesel vehicles started to exhibit higher emissions on the NEDC with hot start than on the NEDC with cold start.

CADC

The Common Artemis Driving Cycle (CADC[6]) has been derived from speed patterns recorded on the road for vehicles operated in normal traffic. It consists of different parts representing urban, rural and highway driving. The CADC is used as a de facto standard for simulating real-world driving on a roller bench by many research organisation throughout Europe, although its speed distribution and dynamics are somewhat more aggressive than would be representative for average real-world driving in the Netherlands and many other countries.

In the period that Euro 5 and Euro 6 vehicles were tested, roller bench tests using the CADC were performed on almost all vehicles that were tested in the laboratory. Over time the CADC was applied in different manners. Initially, a variant of the CADC with a maximum speed of 130 km/h was used. In order to include possible effects of the introduction of the 130 km/h speed limit in the Netherlands in 2011, in the emission testing the low velocity variant of the CADC was replaced by variant with a maximum speed of 150 km/h from 2013 onwards. The urban and rural part of both CADC variants are the same. Also the road load settings were changed over time. Up to the last quarter of 2014 the same road load as for the NEDC was

applied. From the last quarter of 2014 onwards the WLTP road load was used when testing cars on the CADC.

For Euro 5 vehicles laboratory testing on the CADC is found to produce emission results that are representative for the actual emissions occurring in real-world driving on the road, as observed from the limited PEMS testing by TNO of Euro 5 vehicles. This has also been verified by comparing our test results with accurate remote sensing measurements carried out by IVL in Sweden[7].

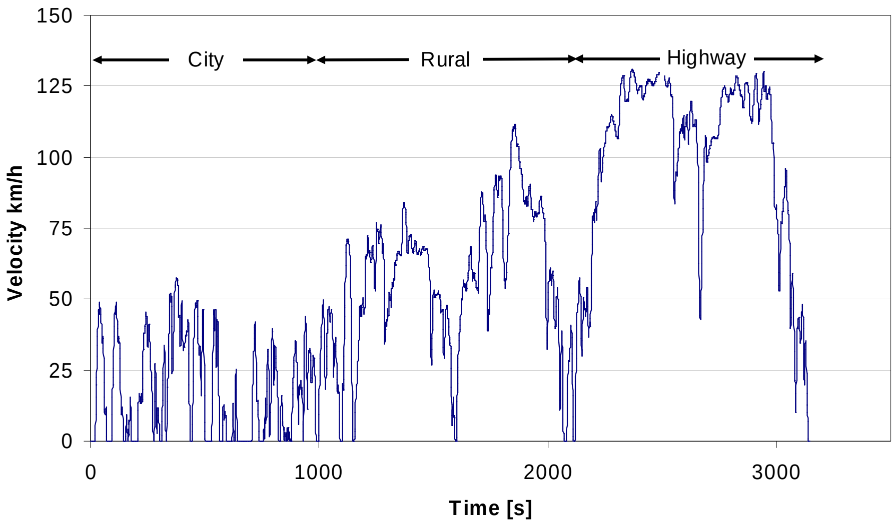


Figure 4 The 130 km/h variant of the CADC (Common Artemis Driving Cycle)

The CADC test is performed under the same temperature conditions as the NEDC-test. Between 2009 and 2012 (starting “halfway” the Euro 4 timeframe) the effect of cold start on vehicle emissions was assessed by performing a CADC with a cold start, immediately followed by driving an additional urban part of the cycle, and comparing the results for the cold and warm urban sub-cycle. Around 2012 also on this test vehicles started to exhibit higher emissions on the warm test than on the test starting with a cold engine, and the method of comparing cold and warm tests was abandoned altogether. As a consequence for modern diesel vehicles it is difficult to assess the real-world cold start effect from either laboratory tests or PEMS tests.

TNO-Dynacycle

In 2008 TNO concluded that the driving cycles commonly used in the laboratory do not cover strong and prolonged accelerations that are sometimes observed in real-world driving. In order to also collect emission data for this type of driving in the laboratory the artificial TNO-Dynacycle was developed. Not all cars have enough power to follow this driving pattern: in that case full throttle driving is used. High emissions on the TNO-Dynacycle are typically associated with shortcomings of the emission control for strong accelerations and their associated high power demand.

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[7] See *Evaluation of European Road transport emission models against on-road emission data as measured by optical remote sensing*, Sjödin, Å., Jerksjö, M. (IVL), (2008) 17th International Transport and Air Pollution Conference, Graz

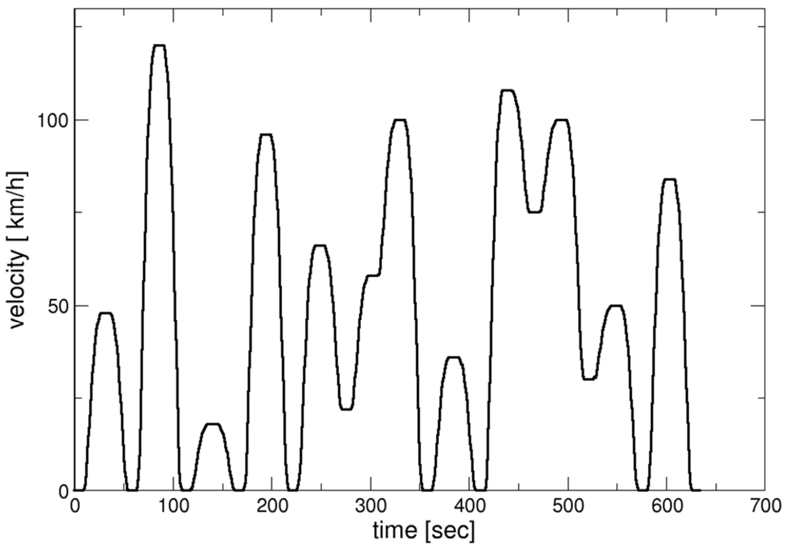


Figure 5 The artificial TNO-Dynacycle, developed for assessing emissions at strong and prolonged accelerations

WLTC
Over the last years the world harmonized light duty test cycle WLTC has been developed as part of the WLTP[5]. From 2013 onwards draft versions of the WLTC have been used by TNO and other institutes in specialized test programs, executed at the request of the European Commission for the evaluation of the protocol and the comparison of the different type-approval tests. TNO has also used the WLTC for its test program for the Ministry of Infrastructure and the Environment. The validation tests were part of a larger test program and generally had a slightly different test protocol compared to the tests which were executed for the Dutch Ministry. In almost all of these tests the road load settings for the roller bench were in accordance with the (draft) procedures prescribed by the WLTP.

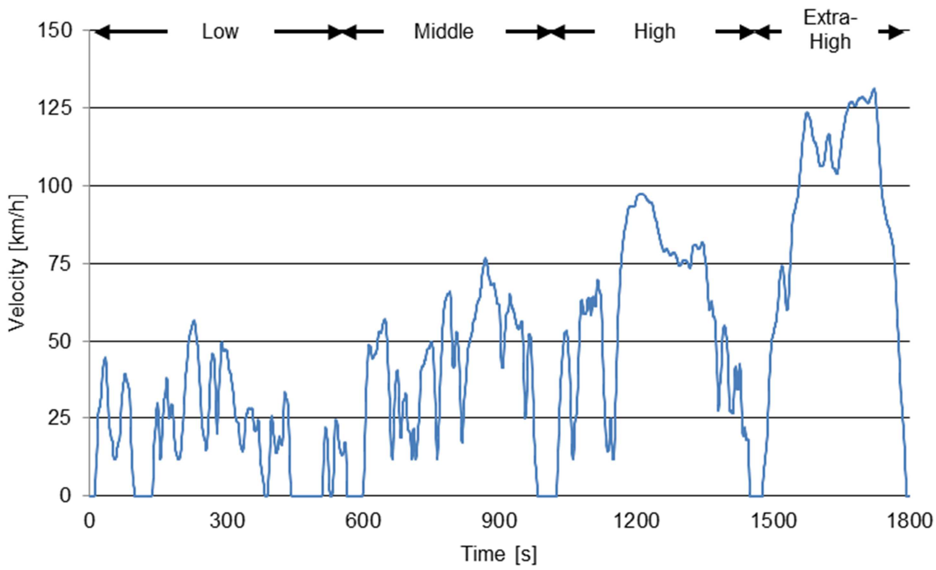


Figure 6 The Worldwide harmonized Light duty driving Test Cycle (WLTC_v5).

The WLTC driving cycle was developed over a number of years, and earlier versions were slightly more aggressive, in terms e.g. accelerations and decelerations, than the final test cycle as defined in the UNECE Global Technical Regulation 15.

Apart from the speed-time profile, four important aspects have to be taken into account, in order to yield a fair comparison of the results and the bandwidth in the testing on the NEDC and WLTC. First of all, the vehicle test mass in the WLTP test procedure is higher than in the NEDC test, and therefore closer to that of production vehicles in actual use. Secondly, the road load is generally higher, in part because of the higher vehicle test mass, but also due to the improved determination of the road load. Thirdly, the testing of a vehicle model on the WLTC occurs in a bandwidth: Given a family of vehicle models, a “low road load” and a “high road load” version has to be tested to establish the bandwidth, within which all vehicle models from the “vehicle interpolation family” should find a place. Finally, in many cases in the validation program appropriate data on weight and road load for the laboratory settings were not available so rough estimates had to be used to allow for testing. In particular, the new table values for road loads, as part of the new regulation, are an extreme worst case setting for the test, corresponding to the worst 3% vehicles. This estimate is meant to be an incentive for determining road loads through measurement, rather than relying on table values. Testing with these table values may increase the emissions significantly.

In an early stage of the WLTP development measurements by TNO have been done using both mass and road load definitions. Later on only the high test mass and road load values were used.

Gear shift strategies
The gear shift points vary from test protocol to test protocol. The NEDC and the TNO Dynacycle have fixed velocities for gear shifts. The CADC also has gear shifts at fixed velocities, but unlike the NEDC these velocities depend on vehicle characteristics such as the rated power. For the WLTP the gear shift strategy to be applied is, within some limitations, determined by the manufacturer. For our measurements, the WLTP tests were executed with gear shift points that were determined using generic tools, developed for and supplied by the European Commission, based on the vehicle and transmission characteristics.

2.3 Measurements on the road

2.3.1 Test facilities

PEMS
With the regulatory developments for on-road testing of heavy-duty vehicles in the USA and Europe, certified mobile measurement equipment, also known as portable emissions measurement system (PEMS), became available from 2008 onwards. In 2010 the European Commission decided that the use of PEMS equipment was also the way forward for the RDE legislation, currently under development, which prescribes on-road testing as part of the type approval test protocol for light-duty vehicles. In response to that, TNO started to gain experience with emission testing of light-duty vehicles on the road. TNO’s previous experience with PEMS-testing of heavy duty vehicles was helpful to arrive at a pragmatic test protocol quickly. As

part of the test protocol a reference test cycle was developed with an appropriate coverage of all relevant driving behaviour and road types.

The PEMS equipment used by TNO for the tests described here is a Semtech DS-version[8]. The way it is mounted in and on vehicles is illustrated in Figure 7.



Figure 7 The PEMS system mounted on vehicles to be tested on the road

PEMS equipment is relatively bulky and heavy, and as a consequence affects the total weight of a light-duty vehicle, tested on the road. The set-up used by TNO weighs around 170 kg, including analysers, battery and generator-set[9], and its operation also requires the presence of a technician in the car besides the driver. The air-resistance and exhaust back pressure are also somewhat affected due to the fixture of a flow tube on the exhaust pipe. The higher mass and resistance affect the fuel consumption and emissions of the vehicle while driving with the PEMS on-board.

TNO always installs the PEMS system inside the vehicle, either in the trunk or in the passenger compartment, dependent on available space. Compared to the alternative of installation on a rack outside the vehicle, this provides a more stable operating environment for the PEMS and thus more stable measurement results.

SEMS

The size, weight, and complexity of the certified PEMS equipment is prohibitive for large monitoring programs. Therefore, soon after starting PEMS testing of heavy-duty vehicles, TNO initiated the development of a simpler measurement technique, tuned towards monitoring the NO_x emissions: the Smart Emissions Measurement System (SEMS[10]). This method uses automotive NO_x and oxygen sensors to estimate the emission performance. Combining measurements of the NO_x and

[8] This is the first generation PEMS equipment. Recently TNO has replaced this by the next generation Horiba OBS system.

[9] Through the use of a generator-set the PEMS' electrical power supply is independent from the vehicle and therefore does not affect the engine load during driving.

[10] For more details on the TNO SEMS system see e.g.:
SEMS operating as a proven system for screening real-world NO_x emissions, R.J. Vermeulen, H.L. Baarbé, L.W.M. Zuidgeest, J.S. Spreen, W.A. Vonk, S. van Goethem (2014),TAP conference Graz.
A smart and robust NO_x emission evaluation tool for the environmental screening of heavy-duty vehicles, R.J. Vermeulen, N.E. Ligterink, W.A. Vonk, H.L. Baarbé (2012), TAP conference Thessaloniki.

oxygen concentrations with the MAF signal (Mass Air Flow) on the OBD (On Board Diagnostics) allows for an accurate, robust, and fast way of measuring absolute emissions on light-duty diesel vehicles. The weight of the system is around 10 kg.



Figure 8 The SEMS system, developed by TNO, mounted on vehicles to be tested on the road (prototype version 2015)

Since this method is not certified, and relies on signals of (in principle) unknown accuracy and origin, the results and sensors are continuously calibrated and compared with results of laboratory testing in cross-validation experiments. The accuracy and reproducibility of measurements with our current generation of SEMS equipment is in most cases within a bandwidth of 10%, and in many cases even within a much smaller bandwidth.

For SEMS testing the vehicles are modified slightly to insert sensors in the tailpipe and connect equipment to the vehicle electronics. However, special care is always taken not to interfere with the normal operation of the vehicle. In one case a manufacturer argued, in response to test results that were sent for evaluation, that the location of an additional sensor may have affected the exhaust gas flow and the readings for emission control from the car's own sensor downstream.

TNO is aware of the variation in quality of automotive NO_x sensors and the possible cross-sensitivity for NH_3. We take account of that in the design and manufacturing of our SEMS devices, and by regular calibration of the systems before and after tests. For vehicles equipped with SCR systems part of the NO_x values, recorded by SEMS, could be attributable to NH_3 slip. The approach used by TNO aims to minimize that share.

TNO uses the PEMS and SEMS measurement method as the basis for determining emission factors for Euro 5 and Euro 6 light commercial vehicles and Euro 6 passenger cars from 2014 onwards.

2.3.2 Trips used for on-road testing

TNO has developed a reference trip for on road testing. This route contains roughly equal parts of urban roads, rural roads and highways.

In addition to this reference trip the on-road test programme usually also contains a large number of trips measuring emissions on different road types under a variety of

traffic conditions. The program often also includes specialized tests such as constant velocity driving, trips to the test laboratory in Germany with parts containing top speeds of around 150 km/h, and driving typical commuting trips.

Both eco-driving and sportive driving was included to the test program for a number of cars. In many cases the traffic did not allow for substantial changes of the average velocity, associated with different driving styles, over the trip.

Table 2 Characteristics of three important routes used in on-road testing by TNO

	TNO City route Helmond	**TNO reference route Helmond**	**Constant speed route Germany**
Type	City	City, rural and highway	Highway
Cold/Hot start	Hot start	Cold and hot start	Hot start
Distance [km]	25.6 km	73.5 km	189 km
Duration [min]	± 57 min	± 89 min	±119 min
Av. speed [km/h]	32 km/h (excl. idle time)	55 km/h (excl. idle time)	93 km/h (total route)*

*) Constant speed measurements are part of this route

On-road testing will show a natural variation in the g/km emissions, even for the repetition of seemingly identical trips. It is only natural to put a bandwidth on this type of data. As a rule of thumb a 15 to 20% variation for similar trips appears natural. A much larger variation can be expected for different trips or for different ambient conditions (incl. e.g. temperature, wind, precipitation) and the related variation in auxiliary use (lighting and air conditioning).

In addition to the above-mentioned trip-to-trip variation a measurement uncertainty of similar order of magnitude is associated with the use of first generation PEMS equipment[11]. Combined with the trip-to-trip variation this leads to an overall variability of the test results for similar trips of around 30%.

Hence, based on the test data, the vehicles tested on the road cannot be ranked easily on the basis of their emissions on a particular test. In the laboratory such ranking, due to the narrow bandwidth of test conditions is more easily established. However, the relevance of the laboratory test data for real-world emissions is limited. Typically, the NEDC tests shows the capabilities of the emission control technology. The typical operation of the emission control technology varies greatly, judging from the emission data both in the laboratory as well as on-road.

2.3.3 *Relation to RDE*

The TNO on-road reference trip predates any trip requirement proposal for RDE legislation[12]. Legal trip requirements for the RDE test have been under development since 2013. However, only from October 2015 the RDE trip requirements were solid enough to develop a TNO RDE-compliant test trip. This new test trip is still

[11] Larger measurement errors of PEMS reported by other parties can be explained by improper installation, the lack of calibration, or faulty equipment. For PEMS measurements a good practice guide is essential.

[12] Real Driving Emissions, see e.g.
http://europa.eu/rapid/press-release_IP-15-5945_en.htm, or
http://ec.europa.eu/growth/sectors/automotive/environment-protection/emissions/index_en.htm

considered within the bounds of typical Dutch driving behaviour. However, some special provisions were taken to ensure a generally valid trip according to the RDE requirements (for the variant “moderate”). Up to the middle of 2015, however, there has been limited testing with this RDE-compliant trip. All of the on-road data presented here are for the original reference trip.

Aspects of the RDE legislation which deviate from the original on-road reference trip used by TNO are:

- The order of road type prescribed for the RDE test is urban→ rural→ motorway. This is unlike the reference trip, which is a round trip starting and finishing in an urban area, with rural and motorway sections in between.
- The driving dynamics in the TNO reference trip, which for urban driving is on the high end of the allowed bandwidth and for the rural driving at the low end of the bandwidth allowed by the RDE.
- The evaluation of the emission data: typically no data is excluded from the measurement on the reference trip and the data is not normalized to a particular standard.
- The fractions of urban, rural and motorway driving in the RDE cover the same distance yielding a long time of urban driving and a short time of motorway driving. In the reference trip the distribution is more skewed distance-wise to achieve a more even sampling in time over the different road types.
- The duration of successive urban, rural and motorway parts of the reference trip is approximately 90 minutes while the duration of an RDE-trip must be 90 to 120 minutes.

2.3.4 Test conditions for on-road testing

Testing on the road is performed all year round, from warm summer days to cold winter days. Temperatures typically range between 0 and 30°C. This variation in ambient conditions is known to affect the emission result of a typical modern vehicle. Extreme weather was typically excluded: snow and sub-zero temperatures are not common in the test data. The on-road temperature, which for average Dutch daytime weather is around 11°C, is much lower than the NEDC test conditions (between 20 and 30°C) and the WLTP target temperature of 23°C. In the laboratory it is generally not possible to test at temperatures outside the legally prescribed range. Hence it is generally not possible in laboratory testing to separate the effects of varying ambient conditions from the effects of other aspects of laboratory tests.

The mass of the vehicle in a road test is the real empty mass of the vehicle, as used in fully operational state, plus:

- the weight of the driver and technician plus 170 kg for analysers, battery, and generator in the case of PEMS;
- the weight of the driver plus < 10 kg for the measurement system in case of SEMS.

During the tests on the road the air conditioning (A/C) is switched on or off dependent on the comfort requirements of the driver, as part of testing under realistic real-world conditions. The A/C use is not recorded. During on-road testing with PEMS, however, the A/C may be used more than what would be representative for daily use of the vehicle due to the heat load of the PEMS and its

generator-set[13] that are sometimes installed in the passenger compartment. The use of A/C generally increases the load on the engine and therefore can increase emissions.

For a test trip with PEMS or SEMS the preconditioning of the vehicle in principle consists of the previous trip plus a limited amount of idling before start of the trip. As previous trips may have different characteristics, this leads to some variation in the starting conditions of the vehicle, its engine and aftertreatment system (e.g. temperature or ammonia storage of the SCR system). Such variations, however, are representative of real world driving. The use of a more standardised preconditioning procedure before every trip could reduce the variability of on-road test results, but would also lead to a bias in the test results compared to average real-world driving.

[13] A generator-set is used to provide electric power to the PEMS system so that it operates independent of the vehicle’s electric system. In this way the energy use of the PEMS does not affect the engine load during driving.

3 Vehicle selection

Most of the Euro 5 and Euro 6 vehicles for this test program were obtained from rental companies. Vehicle models were selected on the basis of the quarterly Dutch national sales figures, combined with the overall popularity of certain vehicle models, and their availability from rental companies.

For the sample of diesel vehicles, of which the test results are reported here, care was taken to make sure that the sample covered a wide range of popular engine types sold on the Dutch market. The overall maintenance state of the vehicles was checked, generally no faults were found. Typical odometer readings were 3.000 – 20.000 km.

For chassis dynamometer tests in the laboratory the road load was obtained from the importer or in some cases the manufacturer, and the weight used for the chassis dynamometer setting was based on the vehicle documentation. For on-road testing the actual weight and tyres of the vehicles were accepted as the proper state.

For Euro 6 passenger cars the selection included three different sets of vehicles[14]:
- Phase 1: available prototypes / US models made up the test program in 2010.
    - These were vehicles intended for the US market equipped with the technology to reduce emissions to Euro 6 level, but that had not (yet) officially been given Euro 6 type approval.
- Phase 2: first Euro 6 production models on the Dutch market, tested in 2013 and 2014.
- Phase 3: selection of Euro 6 vehicles with SCR, tested in 2015.

[14] See e.g.: *Detailed investigations and real-world emission performance of Euro 6 diesel passenger cars*, report number TNO 2015 R10702, 18 May 2015.

4 Results

An overview and specifications of the Euro 5 and 6 diesel passenger cars tested by TNO before May 2015 is provided in Table 3.

Table 4 on the next page presents an overview of the results with respect to NO_x emissions obtained from emission testing of these vehicles in the laboratory and on the road.

For notes with respect to terminology used in the tables see the list after Table 4.

Table 3 Overview and specification of the vehicles tested by TNO before May 2015.

	make	model	fuel	displ. [cc]	power [kW]	Euro class	EGR	LNT	SCR	code	date	number of vehicles	Ambient T [°C] PEMS / SEMS
Passenger cars (Euro 5)	Mercedes	E220 CDI	D	2143	125	5	X	-	-	-	July 2010	3	-
	Renault	Megane Grand Scenic	D	1461	81	5	X	-	-	-	July 2010	3	-
	Peugeot	5008	D	1560	82	5	X	-	-	-	May 2011	1	15 - 21
	Fiat	Punto Evo	D	1248	62	5	X	-	-	-	June 2011	1	15 - 22
	VW	Passat	D	1598	77	5	X	-	-	-	Nov. 2011	2	3 - 9
	Peugeot	207	D	1560	68	5	X	-	-	-	Dec. 2011	1	3 - 7
	VW	Passat CC	D	1968	103	5	X	-	-	-	Jan. 2012	1	-
	VW	Polo	D	1199	55	5	X	-	-	-	Aug.-Oct. 2012	1	11 - 13
	Ford	Mondeo	D	1997	103	5	X	-	-	-	Sept. 2012	1	-
	Opel	Corsa	D	1248	70	5	X	-	-	-	Sept. 2012	1	-
	BMW	320	D	1995	120	5	X	-	-	-	Sept. 2012	1	-
	Renault	Twingo	D	1460	63	5	X	-	-	-	Sept. 2012	1	-
	Volvo	V60 plug-in hybrid	E/D	2400	158	5	X	-	-	-	March 2015	1	6 - 8
Passenger cars (Euro 6)	BMW	330	D	2993	180	6	X	X	-	H2a	May 2010	1	-
	Mercedes	350	D	2997	155	6	X	-	X	A2	July 2010	1	-
	VW	Passat	D	1968	105	6	X	-	X	E4	July 2010	1	-
	BMW	730	D	2993	160	6	X	X	-	H3	Nov. 2010	1	-
	BMW	330	D	2993	180	6	X	X	-	H2b	Nov. 2010	1	-
	BMW	320	D	1995	135	6	X	X	-	H4	Sept. 2012	1	-
	VW	Passat CC	D	1968	103	6	X	-	X	E6	Feb. 2013	1	-1 - 5
	Mazda	CX5	D	2191	110	6	X	-	-	J1/J2	July 2013	2	-
	BMW	320	D	1995	135	6	X	X	-	H6	July 2013	1	-
	BMW	518	D	1995	105	6	X	X	-	H7	Nov. 2013	1	4 - 7
	Opel	Zafira	D	1598	100	6	X	-	X	K1/K2	May-June 2014	2	16 - 25
	Peugeot	308	D	1560	88	6	X	-	X	L1	Nov. 2014	1	8 - 14
	Mercedes	C220	D	2143	125	6	X	-	X	M1	Feb. 2015	1	0 - 4
	BMW	530	D	2993	190	6	X	-	X	O1	Feb. 2015	1	2 - 5
	Audi	Q7	D	2967	180	6	X	-	X	N1	March 2015	1	7 - 9

Table 4 Overview of test results with respect to NO_x emissions per vehicle model for all Euro 5 and 6 diesel passenger cars tested before May 2015.

						chassis dynamometer								PEMS						SEMS					
						NOx emissions [mg/km]								NOx emissions [mg/km]						NOx emissions [mg/km]					
	make	model	fuel	Euro class	TA limit [mg/km]	NEDC cold st.	NEDC hot st.	CADC cold st.	CADC hot st.	CADC 150	dyna hot st.	WLTC cold st.	WLTC hot st.	ref. cold st.	ref. hot st.	city hot st.	all tests avg.	all tests Stdev	distance [km]	ref. cold st.	ref. hot st.	city hot st.	all tests avg.	all tests Stdev	distance [km]
Passenger cars (Euro 5)	Mercedes	E220 CDI	D	5	180	156	-	-	416	-	722	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Renault	Megane Gr.Sc.	D	5	180	305*	-	-	862	-	830	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Peugeot	5008	D	5	180	187	-	-	616	-	918	-	-	598	658	659	599	218	524	-	-	-	-	-	-
	Fiat	Punto Evo	D	5	180	170	-	-	651	-	985	-	-	745	931	1081	823	337	506	-	-	-	-	-	-
	VW	Passat	D	5	180	112	574	680	752	-	908	-	-	741	701	891	738	248	484	-	-	-	-	-	-
	Peugeot	207	D	5	180	-	-	-	-	-	-	-	-	534	600	602	539	255	580	-	-	-	-	-	-
	VW	Passat CC	D	5	180	155	-	933	969	-	1261	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	VW	Polo	D	5	180	161	319	609	618	-	734	-	-	743	554	656	643	371	777	-	-	-	-	-	-
	Ford	Mondeo	D	5	180	249	-	610	632	-	926	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Opel	Corsa	D	5	180	197	-	475	476	-	575	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	320	D	5	180	106	-	168	202	-	392	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Renault	Twingo	D	5	180	296**	-	394	412	-	618	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Volvo	V60 PHEV	E/D	5	180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	453	603	621	639	372	1162
Passenger cars (Euro 6)	BMW	330	D	6	80	36	-	-	97	-	486	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mercedes	350	D	6	80	66	-	-	10	-	119	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	VW	Passat	D	6	80	72	-	-	90	-	134	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	730	D	6	80	35	-	-	181	-	372	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	330	D	6	80	80	-	-	457	-	454	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	320	D	6	80	12	0	205	201	-	257	31	17	-	-	-	-	-	-	-	-	-	-	-	-
	VW	Passat CC	D	6	80	98***	201	177	175	-	493	-	182	420	401	619	294	191	697	-	-	-	-	-	-
	Mazda	CX5	D	6	80	65	89	582	593	663	428	198	226	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	320	D	6	80	27	16	28	26	79	193	-	25	-	-	-	-	-	-	-	-	-	-	-	-
	BMW	518	D	6	80	-	-	-	-	-	-	-	-	467	469	228	507	471	875	-	-	-	-	-	-
	Opel	Zafira	D	6	80	56	60	253	239	301	390	186	435	658	212	657	668	337	970	-	-	-	-	-	-
	Peugeot	308	D	6	80	106	11	122	113	317	-	222	74	330	290	306	299	148	743	384	339	358	339	169	1028
	Mercedes	C220	D	6	80	34	27	27	15	26	-	47	51	565	643	592	665	115	320	532	653	586	622	417	2885
	BMW	530	D	6	80	28	28	16	6	18	-	22	39	-	-	-	-	-	-	169	87	132	123	93	1573
	Audi	Q7	D	6	80	58	214	370	371	279	-	109	211	-	-	-	-	-	-	363	487	606	412	291	3575

Notes:

* The manufacturer has informed TNO that 14 vehicles of this model have been tested in the frame of an in-service conformity (ISC) program under the control of UTAC. UTAC has confirmed to the manufacturer that this model complies with the Regulation, as measured in the frame of ISC checks. Finding the possible causes for the high NOx emissions on the NEDC with cold start measured by TNO would require additional testing, which has not taken place. For that reason, and in view of the ISC results obtained by UTAC, the results from the NEDC tests by TNO cannot be regarded as an indication for non-compliance with the type approval limit for Euro 5.

** A check of the road load after execution of the NEDC test revealed that the road load after the test exceeded the values at which the dynamometer was set at the beginning of the test. In some parts of the coast down test on the roller bench the deviation of coast down times was outside the 5% bandwidth allowed by UN ECE R83. As a result the NEDC test carried out on this vehicle is not a valid replication of the type approval test. For that reason the NOx emission measured on this vehicle by TNO on the NEDC test with cold start cannot be compared with the type approval limit for Euro 5.

*** A check of the road load after execution of the NEDC test revealed that the road load after the test exceeded the values at which the dynamometer was set at the beginning of the test. In some parts of the coast down test on the roller bench the deviation of coast down times was outside the 5% bandwidth allowed by UN ECE R83. As a result the NEDC test carried out on this vehicle is not a valid replication of the type approval test. For that reason the NOx emission measured on this vehicle by TNO on the NEDC test with cold start cannot be compared with the type approval limit for Euro 6.

General notes in relation to Table 3 and Table 4:

- “displ.” in Table 3 stands for engine displacement.
- “power” in Table 3 stands for rated power as specified by the manufacturer
- “code” in Table 3 stands for the identification code used for presenting results on these vehicles in previous reports in which these results have been anonymized.
- “date” in Table 3 stands for the month in which the tests have taken place. In general a test program lasts several days. In many cases different measurements were done on a vehicle in a period of a few weeks.
- “number of vehicles” in Table 3 stands for the number of vehicles of the same make/model/variant that have been tested. If this number is larger than 1, the test results in Table 4 have been averaged over the tested vehicles.
- “Ambient T [°C] PEMS/SEMS” in Table 3 stands for the bandwidth of ambient temperatures during testing of the vehicle on the road with PEMS or SEMS. The temperature ranges indicated here are based on the recordings of the Dutch weather institute KNMI for the region in which the tests took place[15].
- “TA limit” in Table 4 stands for the Type Approval limit applicable to the NEDC test with cold start.
- “cold st.” resp. “hot st.”in Table 4 stand for “cold start” resp. “hot start”.
- “dyna” in Table 4 stands for the TNO-Dynacycle, as described in section 2.2.2.
- The term “avg.” under “all tests” in Table 4 stands for the average emissions determined over all on-road tests carried out with PEMS or SEMS on a given vehicle. Please note that this average is <u>not</u> the average over the three results on the reference trips with cold and hot start and the urban trip, as listed in the table. Instead, this is the average result over all trips measured on the vehicle. This set of trips e.g. also includes trips used for assessing emissions while driving at constant speeds and highway trips assessing emissions at high speeds.
- The term “Stdev” under “all tests” in Table 4 represents the standard deviation associated with the above mentioned average.
- The “distance” in the shaded columns in Table 4 is the total driven distance over which emissions have been monitored using SEMS or PEMS, and also the total distance over which emissions as listed under “avg.” have been averaged.

[15] In most measurements on the road also the ambient temperature reading from a thermometer connected to the PEMS/SEMS system as well as the engine’s air inlet temperature are recorded.

5 General considerations and additional specific information relevant for the interpretation of the presented test results

5.1 General considerations

- The NEDC test with cold start is the so-called Type 1 test from the European type approval test protocol. It is only one of the many tests that must be performed as part of the type approval process, and the emission limit applicable to the test is only a small part of the complete spectrum of vehicle requirements that manufacturers are obliged to comply with. In addition to the Type 1 test also durability testing, low temperature tests and evaporative emissions testing is required. Furthermore Conformity of Production (CoP) testing, also in the laboratory on the NEDC, is part of the legislation to ensure compliance of all production vehicles to the emission standard.
- If the emissions of an individual vehicle as tested by TNO exceed the applicable limit on the Type 1 test, this cannot be interpreted as non-compliance. The European type approval regulation contains provisions for testing the in-service conformity of vehicle models. These describe criteria for vehicle selection (proper maintenance, no indications of abuse, no OBD issues or faults, no evidence of mis-fueling, etcetera), the minimum number of vehicles to be tested, and a procedure for testing a larger number of vehicles and statistical evaluation of the test results if initial tests indicate a possible non-compliance.
- Vehicles tested by TNO are generally in an appropriate state, corresponding to proper maintenance. In most cases, the outcome of the NEDC test according to the official type-approval test protocol shows emissions below, or close to, the emission limit value. This is an indication, no more or less, that the vehicle and its emission reduction technology are in principle in a proper condition and can serve the purpose of this specific monitoring goal. Therefore, the high NO_x emission results observed on a large sample of vehicles in a variety of other laboratory and real-world tests cannot generally be linked to malfunctions of the vehicles.
- In the current legislation vehicles only have to comply with the emission limits on the type approval test. These limits do not apply to emissions measured on the road in real-world driving nor to emissions which are measured in the laboratory by using other driving cycles than the NEDC or other test conditions than the ones specified in UNECE R83.

5.2 Considerations related to variations in test results

- Overall a large variety of parameters and operating conditions may influence the outcome of an emission test in g/km. These parameters and conditions interact in a complex and in general vehicle-specific way, making it difficult to directly relate observed differences between type approval test results and results of other laboratory or on-road testing to specific test conditions or characteristics of the vehicle or its technology and controls without performing specific tests or modelling. The most important factors are:

  - Vehicle weight: roller bench setting or actual weight when measuring on the road, including passengers, luggage and test equipment;
  - Road load, in particular rolling resistance variations with tyre type, tyre pressure, tyre condition, and the road surface (condition) when measuring on the road;
  - Air drag and the variation thereof with temperature, humidity, and precipitation, and the installation of PEMS equipment;
  - The history of the vehicle, including the run-in period of the vehicle (odometer setting) and state of maintenance;
  - The preconditioning of the vehicle, including the tyre pressure of the warm tyres, and the temperature of the engine and the driveline prior to the test;
  - The type of lubricants and the lubricant levels;
  - The loading of the DPF with soot from driving prior to the test;
  - The battery state-of-charge;
  - The running of electric equipment, in particular lights and air-conditioning[16], and the effect of solar radiation and temperature on the power used by the latter;
  - The gear-shift strategy, as well as the motoring and clutch engagement;
  - Engagement of the stop-start system when available and its functioning for the operation mode of the vehicle;
  - The ambient temperature and humidity during the test;
  - The driving cycle in the laboratory, and the variant thereof in the case of the CADC and WLTP;
  - The driving behaviour in general (actual and average speed, dynamics in terms of accelerations and decelerations);
  - Braking strategies in particular when driving within the bounds of a prescribed driving cycle on a chassis dynamometer.
- Based on physical principles associated with NO_x formation in the combustion process, the variations in the (combination of) parameters listed above between the type approval test and driving under real-world conditions in the lab or on the road are not expected to yield an increase in (engine out) NO_x emissions in g/km by a factor of 3 or more as observed, with the exception of stop-and-go traffic in urban areas and velocities above 150 km/h.
- An emission test may have a variety of outcomes, which cannot always be traced back to typical inputs and determinants, either because these are not monitored or because the relation between inputs and emission outputs is not straightforward.
- A well-known example of generally undetected influences is rapid accelerator movements by the driver's foot. These hardly give rise to variations in velocity and the variation is not observable in a 1 Hz signal, but they may strongly increase emissions. One has to resort to 10 Hz signals, and possibly logging of some additional signals, to be able to detect such driver behaviour. TNO does not execute such tests and does not investigate in what artificial manner high emissions can be achieved with different vehicles. Instead TNO aims to mimic normal driving as well as possible.
- Gear shift strategies affect the results of emission tests, both in the lab and on the road. Delayed gear shifting (at high rpm) can cause high emissions,

[16] See section 2.3.4 for a note on the possible additional A/C use in case of on-road testing with PEMS.

although for NO_x emissions not generally so. In some cases higher NO_x emissions have been observed when eco-driving was applied in on-road tests. Gear shifting constitutes an important part of the variation in driving behaviour studied with on road testing. Some variations in emissions are observed, but it is not always the aggressive driving, with high engine speeds, that yields the highest NO_x emissions. For the WLTP the gear shift strategy is not yet fully defined: manufacturers will have freedom in prescribing strategies, and gear-shift indicators can be essential for repeating the future type-approval test according to the prescription of the manufacturer.

- In the state of the vehicle on the test, the battery state-of-charge and the running of electrical equipment are further important aspects that may influence the emission test result. If electrical equipment is running or the battery is depleted prior to the test, the alternator will require work, yielding a higher engine load. This may be a small change compared to the total work but may take the engine away from the conditions of the type-approval test for which modern vehicles seem highly optimized. In some cases the vehicle was specially prepared by TNO to examine this effect, in other cases the effect may have influenced the outcome in an unknown manner. Especially with on-road testing the influence of the running of electric equipment is unknown. It is, however, seldom a deliberate action in the test setup for on-road testing to increase the overall power consumption.

5.3 Additional information on specific vehicles and tests

- On the NEDC with cold start some of the Euro 5 and Euro 6 passenger cars emitted more NO_x than the applicable type approval limit. Exceedances measured on individual vehicles, however, cannot be interpreted as non-compliance with the type approval regulation. The regulations with respect to durability as well as Conformity of Production allow for variations between vehicles and for the emissions of individual vehicles to be higher than the limit. Also the history and state of the vehicles, which is not known in detail, may contribute to the observed emission behaviour on the NEDC.
- As already mentioned above, the Euro 6 vehicles tested in 2010 were vehicles intended for the US market. These vehicles were equipped with the technology to reduce emissions to Euro 6 level, but had not yet officially been given Euro 6 type approval.
- Four of the six Euro 6 vehicles tested in 2014 and 2015 were further investigated by measuring the NO_x emissions before and after the SCR catalyst. These tests revealed that the settings of the engines and the EGR systems have more influence on the vehicles' NO_x emissions than the settings of the SCR systems. For a combined test trip, representing typical Dutch operational conditions, the NO_x emissions in front of the SCR catalyst measured between 650 and 1250 mg/km. Measurements behind the SCR indicated that the SCR systems contribute to the total NO_x reduction by between 400 and 700 mg/km.

With respect to tests of specific vehicle models additional information is provided as listed below. For some vehicles information received from manufacturers is included. TNO regards this information as technically plausible, but has not verified the statements and does not give any judgement on the extent to which explanations provided are acceptable in the light of the emission regulation.

- In the test program for the Volvo V60 plug-in hybrid vehicle different trips were driven over a four day period. In order to get a broad view on the emission behaviour of the vehicle, different drive line modes, types of trips, driving styles and starting conditions were applied. Before the first emission test on day 1 the hybrid battery was fully charged. During the test program no battery charging has been applied.
- With respect to the test result of the Euro 5 Renault Megane Grand Scenic on the NEDC with cold start the manufacturer has informed TNO that 14 vehicles of this model have been tested in the frame of an in-service conformity (ISC) program under the control of UTAC. UTAC has confirmed to the manufacturer that this model complies with the Regulation, as measured in the frame of ISC checks. Finding the possible causes for the high NO_x emissions on the NEDC with cold start measured by TNO would require additional testing, which has not taken place. For that reason, and in view of the ISC results obtained by UTAC, the results from the NEDC tests by TNO cannot be regarded as an indication for non-compliance with the type approval limit for Euro 5.
- With respect to the test result of the Euro 5 Renault Twingo on the NEDC with cold start it is noted that a check of the road load after execution of the NEDC test revealed that the road load after the test exceeded the values at which the dynamometer was set at the beginning of the test. In some parts of the coast down test on the roller bench the deviation of coast down times was outside the 5% bandwidth allowed by UN ECE R83. As a result the NEDC test carried out on this vehicle is not a valid replication of the type approval test. For that reason the NO_x emission measured on this vehicle by TNO on the NEDC test with cold start cannot be compared with the type approval limit for Euro 5.
- With respect to the test result of the Euro 6 Volkswagen Passat CC (vehicle E6) on the NEDC with cold start it is noted that a check of the road load after execution of the NEDC test revealed that the road load after the test exceeded the values at which the dynamometer was set at the beginning of the test. In some parts of the coast down test on the roller bench the deviation of coast down times was outside the 5% bandwidth allowed by UN ECE R83. As a result the NEDC test carried out on this vehicle is not a valid replication of the type approval test. For that reason the NO_x emission measured on this vehicle by TNO on the NEDC test with cold start cannot be compared with the type approval limit for Euro 6.
- The NO_x emissions measured on the road with PEMS on the Euro 6 Opel Zafira may have been affected by high use of the air conditioning. The tests were carried out in a period with high ambient temperatures. The heat load of the passenger compartment was further affected by the heat release of the generator-set, used for powering the PEMS system independent from the vehicle's engine, and the PEMS itself, which were both installed in the passenger compartment.

- With respect to the CADC-test carried out on the Euro 6 Opel Zafira, the manufacturer has informed us that it has carried out similar measurements using the 150 km/h variant of the CADC[17] and that these tests revealed emissions which are about a factor of 2 lower than the result presented in Table 4. Possible origins of this difference have been discussed but a clear reason could at this stage not be identified.
- In real-world trips on the road, performed between 0 and 4°C ambient temperature[18], measurements on the Mercedes-Benz C220 revealed average NO_x emissions of around 650 mg/km, whereas during all chassis dynamometer measurements in the laboratory – including on test cycles other than the type-approval test – the same vehicle consistently produced emissions below the Euro 6 limit of 80 mg/km. The manufacturer has indicated to TNO that at these low ambient temperatures engine protection functions are active which cause the observed results, and that those engine protection functions are necessary to avoid serious engine damage.

[17] Using the worst case option for the tyre resistance and an inertia setting of the roller bench one weight class higher than the NEDC weight class (IWC+1).
[18] The temperature ranges indicated here are based on the recordings of the Dutch weather institute KNMI for the region in which the tests took place.

6 Observations and interpretation

6.1 General caveats with regard to interpretation of the test results

- The tests performed by TNO are not intended nor suitable for enforcement purposes and are not suitable for identifying or claiming fraud or other vehicle-related irregularities in a technically and legally watertight way. The observed high NO_x emissions under real-world test conditions can and should therefore not be interpreted as an indication for the use of so-called “defeat devices”, “cycle beating” or other strategies that are prohibited by European vehicle emission legislation. Instead the test program has been designed to generate insight in the overall real-world emission behaviour of vehicles, required for environmental policy making and evaluation, as well as inputs for the activities of the Dutch government in the context of decision making processes for improving vehicle emission legislation and the associated test procedures.
- For each make or model, only a single vehicle or a small number of vehicles are tested, which means that it cannot be ruled out that the results correlate to the specific condition of the tested vehicles.
- Emission numbers reported in Table 4 are values as they occur on a range of tests. Emission results for on-road tests are emissions of specific individual vehicles as they occur under the varying operating conditions that have been measured on the road. The results in Table 4 cannot be interpreted or used as emission factors. Emission factors are estimates of the overall average emissions of a specific vehicle class, or of the average emissions of a specific vehicle class under specific average driving conditions on a specified road type. TNO determines emission factors for road vehicles based on analysis of the detailed emission behaviour (emissions as function of speed and driving dynamics) measured on a sufficiently large number of different vehicles from the same class, combined with detailed speed-time profiles that are representative of the average driving behaviour for the road types and traffic conditions for which these emission factors are determined.
- The ratio of real-world NO_x emissions over the NEDC value cannot be directly compared with the so-called Conformity Factor as defined in the RDE. In the RDE regulation the Conformity Factor is applied to an aggregated test result that is derived from the raw test data using a prescribed filtering tool. The real-world data in this report are unfiltered results based on total emissions measured over the lab test or road trip divided by the distance driven. Furthermore, as explained in section 2.3.3, RDE trips need to be within a certain bandwidth of driving circumstances and behaviour as well as ambient condition, and need to have a prescribed structure. The real-world trips used by TNO do not necessarily meet these requirements.
- Because of the myriad of factors that determine the outcome of a real-world emission test, the values reported in Table 4 cannot easily be used to rank vehicles with respect to their emission performance. The influence of differences in the tests executed on two vehicles may be larger than the difference in actual performance of engine, exhaust aftertreatment and control systems.

- Numbers and bandwidths mentioned in the conclusions below are based on the data as presented in Table 4. These data are in many cases averages over a number of trips or over longer trips. The numbers and bandwidths specified here may therefore deviate from values mentioned in previous reports, which were often based on variations in the detailed test results underlying the aggregates reported in Table 4. Please note in this respect the high standard deviations of the on-road emission measurements on Euro 6 passenger cars listed in Table 4. These are of almost the same size as the average values, indicating that on some trips vehicles actually produce very low emissions while on other trips they can easily be twice as high as the average.

6.2 General observations

- Overall it is observed that NO_x emissions of Euro 5 and 6 passenger cars as measured under real-world conditions in the lab or on the road are significantly higher than the values measured on the type approval test or the limit applicable to that test.
- This emission behaviour is seen across wide range of makes and models.
- These test results confirm the results of earlier studies on vehicles up to Euro 4: diesel vehicles comply with type approval requirements on the type approval test, but produce far higher NO_x emissions under real-world driving conditions. The results seem to indicate that the trend of a growing difference between type-approval and real-world emissions continues, at least up to Euro 5.
- In the past, the difference between type approval and real-world emissions could be partly linked to a difference in driving behaviour and conditions between the real world and the type approval tests. Nowadays, the real-world NO_x emissions are higher, even when a vehicle is driven under conditions that are comparable to the type approval test conditions. For example, higher NO_x emissions are observed when starting a type approval test with a hot engine.
- Detailed measurements on a limited number of vehicles, in which emissions were measured in front of as well as behind the SCR, indicate that the SCR is functioning under all conditions and is providing a more or less constant absolute level of reduction (difference in g/km in front of and behind SCR). This suggests that the high real-world emissions observed on these vehicles, and the large variation therein, is most likely related to the operation of engine components such as injection and EGR in response to operating conditions and the applied control strategies.

Euro 5 passenger cars

- Under real-world conditions the NO_x emission of Euro 5 diesel passenger cars, as measured by TNO in the lab on the CADC as well as on the road using PEMS, range on average from around 400 to 1000 mg/km. These values are a factor of 3 to 5 higher than the values measured on the type approval test.
- Only one vehicle, that was tested in the lab only, showed emissions on the real-world CADC test cycle of around 200 mg/km that were closer to the type approval limit.
- On average the real-world NO_x emissions of Euro 5 diesel passenger cars are quite similar to those of Euro 1 to 4 vehicles. The lowering of the NO_x emission

limit on the NEDC by a factor of 5 between Euro 1 and 5, has not resulted in significant reductions of the real-world NO_x emissions of diesel passenger cars.

- The tested plug-in hybrid diesel vehicle produced real-world NO_x emissions that range from 400 to 600 mg/km, which is in line with the bandwidth observed for conventional Euro 5 diesel cars. Starting a 40-kilometer trip with a fully-charged battery resulted in a trip-average NO_x emission of around 400 mg/km. Executing the same trip with an uncharged hybrid battery resulted in trip-average NO_x emissions of 500 to 600 mg/km.
- Very high emissions are generally seen on the TNO-Dynacycle, which simulates prolonged strong accelerations. This might be the result of failing emission control at high power demand, or limited emission control optimization for such artificial driving with strong accelerations.

Euro 6 passenger cars

- TNO measured the emission levels of a range of Euro 6 diesel passenger cars, both in the laboratory and on the road. Overall the tests reveal that on the type-approval test all these vehicles meet the Euro 6 NO_x standard of 80 mg/km. Under real-world conditions, evaluated using the CADC and WLTC on the roller bench or by on-road testing using PEMS or SEMS, the NO_x emissions of the various types of Euro 6 diesel vehicles range on average from 100 to 700 mg/km.
- In 2010 four pre-production Euro 6 diesel passenger car models were tested only on a chassis dynamometer. These were vehicles intended for the US market equipped with the technology to reduce emissions to Euro 6 level, but that had not yet officially been given Euro 6 type approval. On the CADC test cycle, which is closer to real-life conditions than the NEDC, most vehicles performed relatively well with emissions between 10 and 180 mg/km, but one vehicle emitted close to 460 mg/km.
- In 2013 six production diesel passenger cars with various technologies (including EGR and LNT or EGR-only) were tested on the chassis dynamometer as well as on the road. The real-world NO_x emissions of these vehicles varied considerably from around 80 to 730 g/km. The average real-world NO_x emissions of the majority of the vehicles were between 300 and 500 mg/km.
- In 2014 and 2015 six production vehicles with EGR and SCR technology were tested on the chassis dynamometer and extensively on the road. Also for these Euro 6 vehicles the real-world NO_x emission varied strongly and in almost all cases the readings were much higher than the laboratory test results. The average real-world NO_x emissions ranged between 300 to 670 mg/km.
- One of the six vehicles, a BMW 530, produced relatively low average real-world NO_x emissions of 120 g/km on the road and values around 30 mg/km in the lab. This vehicle achieved these real-world NO_x emissions due to low NO_x emission levels directly from the engine of around 650 mg/km, combined with a NO_x reduction of around 500 mg/km in the SCR system. The results of this investigation reveal that low real-world emissions of Euro 6 diesel vehicles are possible with effective settings of the engine and the EGR system in combination with an SCR system that has sufficient potential to reduce NO_x emissions.

- Also for Euro 6 vehicles emissions on the TNO-Dynacycle are generally higher than on other test cycles used in the lab, but the difference is less pronounced than for Euro 5.

6.3 Concluding remarks

It should be re-emphasized that the main objective of the project, of which detailed results are reported here, is not to evaluate the compliance of individual vehicles or vehicle models with emission legislation, nor to perform a comparative assessment of the environmental performance of individual models. Due to the limitations of the test programme, and especially in view of the myriad of factors that affect results of emission testing on the road, drawing conclusions with respect to origins of the emission behaviour of individual models or brands is not justified unless a significant specific testing effort is added.

The main conclusion from the work of TNO for the Dutch Ministry of Infrastructure and the Environment is that subsequent lowering of the type approval emission limits between Euro 1 and Euro 5 by a factor of 5 has not led to substantial reductions of the NO_x emissions of diesel passenger cars and vans on the road[19]. The tested Euro 6 passenger cars appear to have somewhat lower real-world NO_x emissions than Euro 5 vehicles, but definitive conclusions on the effectiveness of the current Euro 6 standard can only be drawn after testing a larger number of models including those in the medium and smaller size segments.

In the Netherlands the high real-world NO_x emissions of diesel vehicles, as reported here and in previous reports, are fully taken into account in the official emission factors that are used in the design and evaluation of national, regional and local air quality measures. The results reported here therefore do not lead to new insights regarding the extent to which European air quality standards are met in the Netherland, nor regarding the effectiveness of specific air quality measures taken by national, regional and municipal governments.

[19] See: *Emissions of nitrogen oxides and particulates of diesel vehicles*, report number TNO 2015 R10838, 11 June 2015

7 Previous reports on NO_x emissions of diesel cars

Results presented in this report are based on research of which the results have previously been published in the reports listed below:

- Verkennende metingen van schadelijke uitlaatgasemissies van personenvoertuigen met Euro-6 dieseltechnologie (in Dutch), report number MON-RPT-2010-02278, 8 September 2010.
- Determination of Dutch NO_x emission factors for Euro-5 diesel passenger cars, report number TNO 2012 R11099, 7 December 2012.
- Investigations and real world emissions performance of Euro 6 light-duty vehicles, report number 2013 R11891, 5 December 2013.
- Detailed investigations and real-world emission performance of Euro 6 diesel passenger cars, report number TNO 2015 R10702, 18 May 2015.
- Uitstoot van stikstofoxiden en fijnstof door dieselvoertuigen (in Dutch), report number TNO 2015 R10733, 26 May 2015.
- Emissions of nitrogen oxides and particulates of diesel vehicles, report number TNO 2015 R10838, 11 June 2015.
- Emission performance of a diesel plug-in hybrid vehicle, report number TNO 2015 R10858 v1, 19 June 2015.

These reports are available from www.tno.nl.

8 Abbreviations

CADC	=	Common Artemis Driving Cycle
CO_2	=	carbon dioxide
DPF	=	Diesel Particulate Filter
EGR	=	Exhaust Gas Recirculation
FTP	=	Federal Test Procedure (= US test protocol)
HD	=	heavy duty vehicles (trucks and buses)
LNT	=	lean NO_x Trap
LD	=	light duty vehicles (passenger cars and vans)
NEDC	=	New European Driving Cycle
NH_3	=	ammonia
NO_x	=	nitrogen oxides
PEMS	=	Portable Emission Measurement System
RDE	=	Real Driving Emissions
RDW	=	Rijksdienst voor het Wegverkeer (Dutch road-vehicle authority)
RW	=	real-world
SEMS	=	Smart Emission Measurement System
SCR	=	Selective Catalytic Reduction
TNO	=	Netherlands Organization for Applied Research
WLTC	=	Worldwide harmonized Light duty driving Test Cycle
WLTP	=	Worldwide harmonized Light vehicles Test Procedures

9 Signature

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TNO





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